COST ANALYSIS OF OXYGEN RECOVERY SYSTEMS

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Contract No. NAS8-28377

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SECTION 1

INTRODUCTION AND SUMMARY

1.0 INTRODUCTION

The design and development of equipment for flight use in earth-orbital programs proceed through a logical progression from bench testing on breadboard units, fabrication and evaluation of prototype equipment, redesign to meet flight imposed requirements, qualification testing, and incorporation into a flight-ready system. Each of these steps is intended to produce the basic design information necessary to progress to the next step. The cost of each step is normally substantially less than that of the following step. Consequently, the knowledge of cost estimates of new technology programs was found to be of great importance to cognizant agencies prior to embarking on new programs.

In order to assist NASA/MSFC in long-range planning and allocation of resources in a cost effective manner in support of earth orbital programs, a methodology has been developed to predict the relevant contributions of the more intangible cost elements encountered in the development of flight qualified hardware based on an extrapolation of past hardware development experience. Major items of costs within life support subsystems have been identified and related to physical and/or performance criteria. Cost and performance data from Gemini, Skylab, and other aerospace and biotechnology programs were analyzed to identify major cost elements required to establish cost estimating relationships for advanced life support subsystems.

This report deals with the cost analysis of four leading oxygen recovery subsystems which include two carbon dioxide reduction subsystem, namely Sabatier and Bosch, and two water electrolysis subsystems, namely, the solid polymer electrolyte and the circulating KOH electrolyte.

2.0 APPROACH

The four oxygen recovery systems have been quantitatively evaluated. System characteristics, including process flows, performance and physical characteristics were also analyzed. Additionally, the status of development of each of the systems considered and the required advance technology efforts required to bring conceptual and/or pre-prototype hardware to an operational prototype status were defined. Intimate knowledge of the operations, development status, and capabilities of the systems to meet space mission requirements were found to be essential in establishing the cost estimating relationships for advanced life support systems.

The following is a summary of the technical approach used. Included are the cost estimating techniques, the development of cost estimating relationships and the development of oxygen systems cost estimates.

2.1 COST ESTIMATING TECHNIQUES

The oxygen recovery systems cost estimating techniques were developed by 1) identifying the physical and performance characteristics of each of the system components; 2) establishing or utilizing existing cost estimating relationships (CER's) for each of the components considered; and 3) the summation of equations for respective system components to establish the total system cost estimation. The U. S. Bureau of Standards Consumer Price Index was used to account for inflation and economic escalation.

2.2 DEVELOPMENT OF COST ESTIMATING RELATIONSHIPS

The methodology used in the development of CER's is as follows:

1. The components were analyzed to determine which physical or performance characteristics might prove useful as predictive variables.

2. Costs were arrayed graphically against the candidate variables either singly or grouped. The most promising of these arrays were selected on the basis of a subjective analysis which considers the appropriateness of the variables, the form and slope of the curves, and the relative aspects of the component costs.

2.3 OXYGEN RECOVERY SYSTEM COST ESTIMATES

A system schecmatic and a component identification list were prepared for each of the four oxygen recovery systems. System and process descriptions, including system performance and characteristics, were also given. The physical and performance parameters were identified for use in formulating the cost estimating relationships. Recurring CER's were then developed and computed for each of the system subassemblies and summed up to obtain the integrated system recurring cost estimates. The system's non-recurring CER's were computed on an integrated system basis. The major influencing parameter for the non-recurring CER's was found to be the number of component types in the system. A summary of oxygen recovery recurring CER's is presented in Table A.

2.4 OXYGEN RECOVERY PROTOTYPE COST ESTIMATES:

A methodology has been developed to provide cost estimates of the following types of prototypes:

1. Low-fidelity prototypes: Made of flight-type , but not flight weight hardware, these prototypes are developed to prove operational performance when integrated with an operational life support system.

2. High-fidelity prototypes: these are flight-qualifiable units which have not undergone flight testing. Cost estimates of low-and high-fidelity prototypes were found to be approximately 5 and 10.2% of qualified subsystem costs, respectively. Estimated costs of flight-qualified and prototype oxygen recovery subsystems were found to be as follows:

	SABATIER	BOSCH	SPE ELECTROLYSIS	KOH ELECTROLYSIS
Low-Fidelity Prototype	220,500	232,100	415,300	358,800
High-Fidelity Prototype	449,860	473,414	847,155	731,899
Flight-Qualified Subsystem	4,410,389	4,641,306	8,305,438	7,175,485

TABLE A - OXYGEN RECOVERY SUBSYSTEM

RECURRING COST ESTIMATING

ASSEMBLY	COST ESTIMATING RELATIONSHIP (FABRICATION COST, DOLLARS)
A. SABATIER CO_2 REDUCTION SUBSYSTEM	
1. Reactor Assembly	$C = 159\ W^{0.267}\ N_p^{1.905} + 3900\ W_{oc}$
2. Blower	$C = 38.2\ P^{0.942} + 2192\ W_{oc}$
3. Condenser/Separator	$C = 159\ W^{0.267}\ N_p^{1.905} + 2959\ W_{oc}$
4. Accumulator	$C = 1{,}918 V^{0.267} + 2959\ W_{oc}$
5. Pump	$C = 91\ P^{0.942} + 670\ W_{oc}$
6. Controller	$C = 4795\ W$
B. BOSCH CO_2 REDUCTION SUBSYSTEM	
1. Reactor Assembly	$C = 159\ W^{0.267}\ N_p^{1.905}\ Q^{0.89} + 3900\ W_{oc}$
2. Compressor	$C = 38.2\ P^{0.942}$
3. Condenser/Separator	$C = 159\ W^{0.267}\ N_p^{1.905} + 2959\ W_{oc}$
4. Accumulator	$C = 1918\ V^{0.267} + 2959\ W_{oc}$
5. Pump	$C = 91\ P_w^{0.942} + 670\ W_{oc}$
6. Controller	$C = 4795\ W$

TABLE A - OXYGEN RECOVERY SUBSYSTEM (Continued)

ASSEMBLY	COST ESTIMATING RELATIONSHIP (FABRICATION COST, DOLLARS)
C. SPE ELECTROLYTE SUBSYSTEM:	
1. Electrolysis Modules	$C = (6250\ W_M + 2192\ W_{oc} + 2000)\ Q^{0.89}$
2. Pumps	$C = 91\ P_w^{0.942}\ Q^{0.89} + 670\ W_{oc}$
3. Deionizers	$C = 200\ W_o\ Q^{0.89} + 670\ W_{oc}$
4. Power Conditioner/Coldplate	$C = (14.9\ P^{0.942} + W^{0.267} N_p^{1.905}) Q^{0.89}$
5. Condenser/Separator	$C = 159\ W^{0.267} N_p^{1.905} Q^{0.89} + 2959\ W_{oc}$
D. CIRCULATING KOH ELECTROLYTE SUBSYSTEM:	
1. Electrolysis Modules	$C = (6250\ W_M + 2000) Q^{0.89} + 2192\ W_{oc}$
2. Electrolysis Modules	$C = 38.2\ P^{0.942} + 2192\ W_{oc}$
3. Reservoir	$C = 1918\ V^{0.267} + 2959\ W_{oc}$
4. Pumps	$C = 91\ P_w^{0.942}\ Q^{0.89} + 670\ W_{oc}$
5. Heat Exchanger	$C - 159\ W^{0.267}\ N_p^{1.905} + 2959\ W_{oc}$

OXYGEN RECOVERY SYSTEM

RECURRING COST ESTIMATING RELATIONSHIPS (Continued)

TOTAL HARDWARE COST $C_T = \sum_{Q=1}^{N} F_A \, F_I \left(\sum_{I=1}^{M} C_I \right) Q^{(1-B)}$ DOLLARS

WHERE

N = NUMBER OF UNITS PURCHASED

F_A = COMPONENT ASSEMBLING FACTOR

F_I = ASSEMBLY INTEGRATION FACTOR

M = NUMBER OF COMPONENTS IN ASSEMBLY

C_I = COMPONENT FABRICATION COST

B = LEARNING CURVE SLOPE

Section 2

COST ESTIMATING TECHNIQUES

The methodology used in establishing cost estimating techniques for life support systems is based on 1) the identification of the physical and performance characteristics of each of the system components, 2) establishing or utilizing existing cost estimating relationships (CER's) for each of the components considered, and 3) the summation of equations for respective system components to establish the total system cost estimation. CER's developed in contract NAS9-9018 were used, with appropriate modifications, to estimate the cost of the components considered. For example, a gaseous storage tank CER was used for the CO_2 accumulator and the LiOH canister CER was used for the silica gel, molecular sieve, and regenerable solid desiccant canisters. The costs of small components such as manual and sequence valves were made on a weight basis. An assembly factor for integrating the components was also used.

Definition of the cost element structure and the application of the CER's are given in the following paragraphs.

COST ELEMENT STRUCTURE:

The cost element structure provides visibility of the total project expenditures and permits identification of the significant project costs. Expenditures are divided into nonrecurring and recurring:

Nonrecurring - The nonrecurring expenditures for each life support subsystem are segregated into Prime Contractor and Major Subcontractor efforts. The Prime Contractor effort involves specification, coordination and integration of the system into the spacecraft. The Major Subcontractor effort is divided into Design and Development, AGE, Program Management and System Engineering, Test Operations and Hardware. The Design and Development costs are segregated into major subsystems.

Recurring - The recurring expenditures are divided into the Prime Contractor and Major Subcontractor costs. The Prime Contractor efforts involve primarily the incorporation of the life support systems into the spacecraft. The Major Subcontractor costs are broken into Sustaining Engineering, Tooling and System Production. The System Production expenditures are segregated into subsystems and these are in turn segregated into components.

Table I presents a typical breakdown of the life support system expenditures, as encountered in the Gemini Program, divided in the respective non-recurring and recurring items. The major nonrecurring costs are those related to Design, AGE, and Prime Contractor's specification and procurement efforts. The major recurring cost item is that of flight hardware production.

EFFECT OF INFLATION ON COST ESTIMATES:

A major inherent feature of the methodology which is highly critical to the accuracy of the results obtained pertains to inflation and economic escalation. Since computed CER's are based on specific year dollars, they must be inflated to the proper year in order to obtain realistic future program values. Due to the lack of a specific aerospace price index, the yearly dollar value adopted in this report was considered to correspond to the Consumer Price Index. Figure 1 shows the Consumer Price Index based on data published by the U.S. Bureau of Statistics.

TABLE I - REPRESENTATIVE LIFE SUPPORT SYSTEM EXPENDITURE BREAKDOWN

NON-RECURRING	%	RECURRING	%
Design	16.68	Flight Hardware Production	54.56
Subcontractor General & Administrative	8.62	Subcontractor G&A	9.22
Subcontractor Fee	3.62	Subcontractor Fee	3.88
Program Management	1.24	program Management	1.36
System Engineering	5.25	Sustaining Engineering	1.96
Development Test	3.44		
Qualification Test	2.54		
Reliability Test	4.09		
AGE	18.45		
Tooling	3.87	Sustaining Tooling	1.69
Non-accountable Test Hardware	1.67		
Specifications, Vendor Coordination and Procurement Expenses	13.62	Specifications, Vendor Coordination and Procurement Expenses	15.49
System Integration	8.36	System Integration	7.15
Prime's Testing	8.17	Minor Subcontracts	4.69
Minor Subcontracts	0.38		
TOTAL	100%		100%

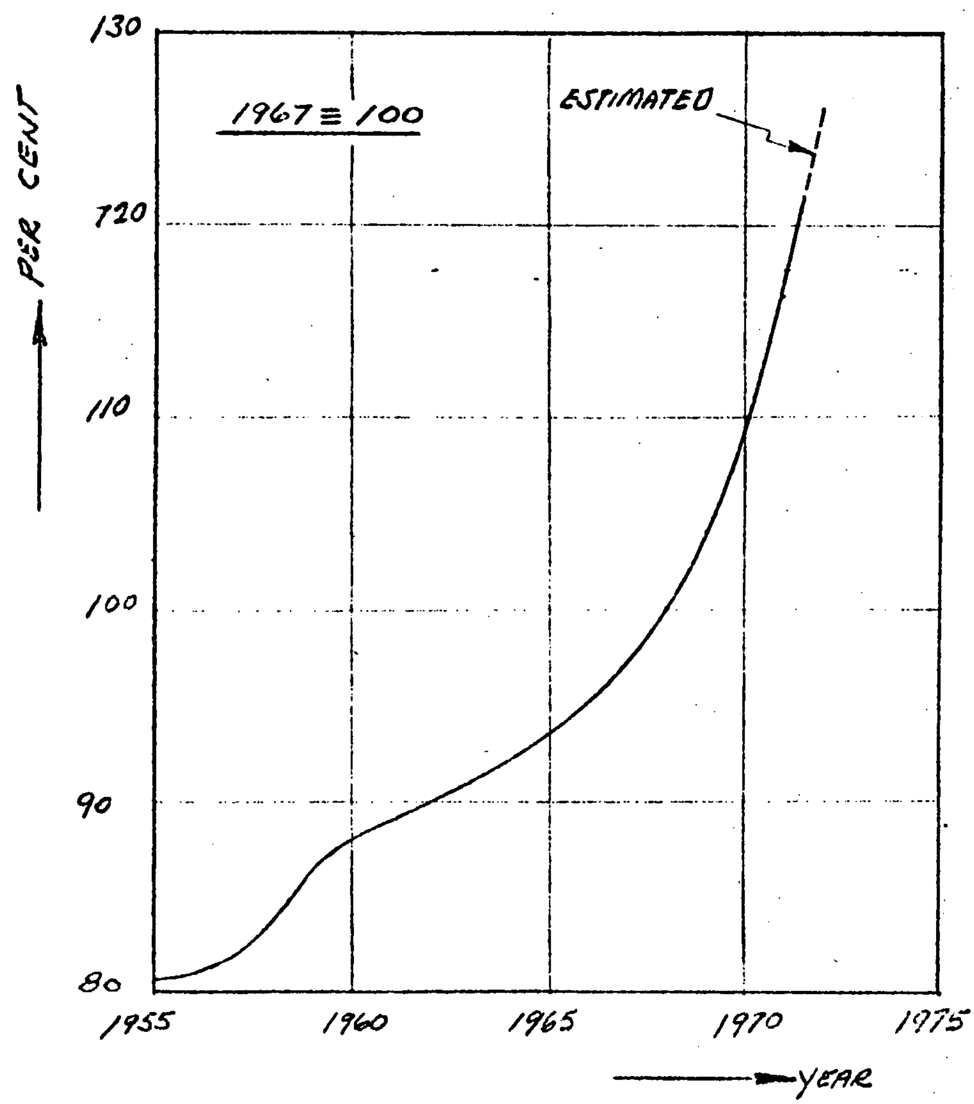

FIGURE I - Consumer Price Index
(Source: U. S. Bureau of Labor Statistics)

SECTION 3

OXYGEN RECOVERY PROCESS COMPARISONS

Oxygen may be recovered from exchaled c arbon dioxide by a number of physico-chemical processes by the reduction of CO_2 to carbon or methane and water, followed by the electrolysis of water to metabolic oxygen and hydrogen. Direct conversion of CO_2 to carbon and oxygen has also been under investigation. However, solid electrolyte which is the leading direct conversion process has not been yet proven operationally feasible and thus will not be discussed in this report. Oxygen recovery processes considered are the following:

1. Sabatier CO_2 reduction
2. Bosch CO_2 reduction
3. Solid polymer electrolyte water electrolysis
4. Circulating KOH electrolyte water electrolysis

Either one of the CO_2 reduction processes may be combined with one of the two water electrolysis methods to attain oxygen recovery from CO_2 . The Sabatier process has been operated successfully in two consecutive manned simulator tests of sixty and ninety days in duration. The methane produced in the Sabatier process leads to the loss of large amounts of hydrogen, when it is vented overboard. The Bosch process, by contrast, produces solid carbon and water and requires no hydrogen make-up for continuous operation. An operational drawback to the Bosch process is the deposition of solid carbon on the reactor. This problem has been partially allevaited by the use of expendable cartridges containing the required catalyst. The Bosch process has been bench-tested, but has not undergone any extended tests as a part of integrated manned life support systems to prove its operational feasibility.

Of the two water electrolysis methods, only the KOH electrolyte subsystem has undergone integrated manned testing. The SPE process has been life-tested and currently appears to be more promising in performance and less troublesome in operation than processes utilizing KOH electrolyte. Oxygen recovery system criteria for the four systems considered are presented in Tables B and C which also present the relative characteristics, operational differences and status of each of the four subsystems.

TABLE B - COMPARISON OF CARBON DIOXIDE REDUCTION SUBSYSTEMS

SUBSYSTEM CHARACTERISTICS	SABATIER CO_2 REDUCTION SUBSYSTEM	BOSCH CO_2 REDUCTION SUBSYSTEM
Crew Size	6 Men	6 Men
CO_2 Processed, Average	2.2 lbs./Man-day	2.2 Lbs./Man-day
CO_2 Delivery Purity	98%	99%
Reactor Operating Pressure	30 to 40 Psia	15 Psia
Condenser Coolant	Water	Water
Coolant Inlet Temperature	50°F	40°F
Water Produced	5.4 Lb/day	10.8 Lb/day
System Operation	1. CO_2 and hydrogen react over Ni or Ru catalyst at 500-700°F to produce CH_4 and H_2O. 2. Water separated in a Water/Gas separator and routed to electrolysis unit. 3. H_2 from electrolysis returned to reactor.	1. CO_2 and H_2 react over expendable iron catalyst at 1200°F to produce carbon and water. 2. Water separated and routed to electrolysis unit. 3. H_2 from electrolysis returned to reactor.
System Status/Availability	1. Low-Fidelity prototypes developed and sucessfully operated in NASA 60 and 90-day tests. 2. Low temperature catalysts developed by Wright-Patterson AFB.	1. Units developed utilizing both rotating and expendable cartridge catalysts. 2. Integrated system test to prove operational feasibility required.
Operational Problems	1. Reactor temperature control	1. Carbon deposition 2. CO_2 purity

TABLE C - COMPARISON OF WATER ELECTROLYSIS SUBSYSTEMS

SUBSYSTEM CHARACTERISTICS	SPE ELECTROLYTE SUBSYSTEM	CIRCULATING KOH ELECTROLYTE SUBSYSTEM
Crew Size	6 Men	6 Men
O_2 Requirement	14.0 Lbs./Day	14.0 Lbs/Day
H_2 Supply Rate	1.57 Lbs./Day	1.56 Lbs.Day
O_2 Outlet Pressure Range	0. to 14.7 Psia	21 to 27 Psig
H_2 Outlet Pressure Range	0 to 40 Psia	9 Psig
Coolant	Water	Water
Coolant Flow Rate	60 Lbs./Hr	0.5 GPM
Feed Water Inlet Temperature	50 to 160°F	50 to 160°F
System Operation	1. Electrolyte is ion exchange plastic sheets.	1. Electrolyte is 35% KOH in water, held in asbestos matrix between electrodes.
	2. Water fed to cathode side only	2. Electrolyte circulated thru matrix and cooled by external heat exchanger
	3. System operated normally at 200 ASF, may operate up to 1000 ASF and 700 psig discharge gas.	
System Status/Availability	1. One-man module bench-tested for 1500 hours.	1. A 4-Man subsystem developed and tested in NASA 90-day test and in 180-day life-test.
	2. Six-man prototype under development	
Operational Problems	Subsystem requires life testing and integrated manned life support system testing	Subsystem requires additional development and repackaging

Section 4

COST ESTIMATES OF OXYGEN RECOVERY SYSTEMS

4.1 SABATIER CARBON DIOXIDE REDUCTION SYSTEM

Process Description:

The Sabatier process involves the hydrogenation of CO_2 over a 400 to 700°F catalyst in a reactor. The Sabatier reaction is summarized by the following equation:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2H_2O + \text{Heat}$$

The Sabatier water product is electrolyzed to oxygen, for breathing, and to hydrogen for return to the Sabatier reactor.

The primary components of the Sabatier reactor include a CO_2 pressure regulator, H_2 and CO_2 mixture control valves, a catalytic reactor bed, a reactor pressure control valve, and a zero-g condenser/water separator. An electric heater also is provided in the Sabatier cooling air inlet line for reactor startup operations only. A schematic of the unit is presented in Figure 2.

The Sabatier reactor obtains CO_2 at an accumulator pressure of 30 to 40 psia. The CO_2 flows through the pressure regulator, which obtains a pressure reference from the H_2 supply. The regulated CO_2 then flows through a control valve under critical flow conditions. The H_2 flows directly to a separate critical flow-control valve. The two gas streams mix downstream of the control valves and then flow into the reactor. The reactor is a jacketed cylinder; the inner cavity contains the catalyst. Nickel-on-Kiesleguhr has been used as a catalyst, usually operated at 700°F. Other catalysts have also been investigated. The most promising are the noble metals such as ruthenium, which operates in the 450 to 600°F range, and rhodium.

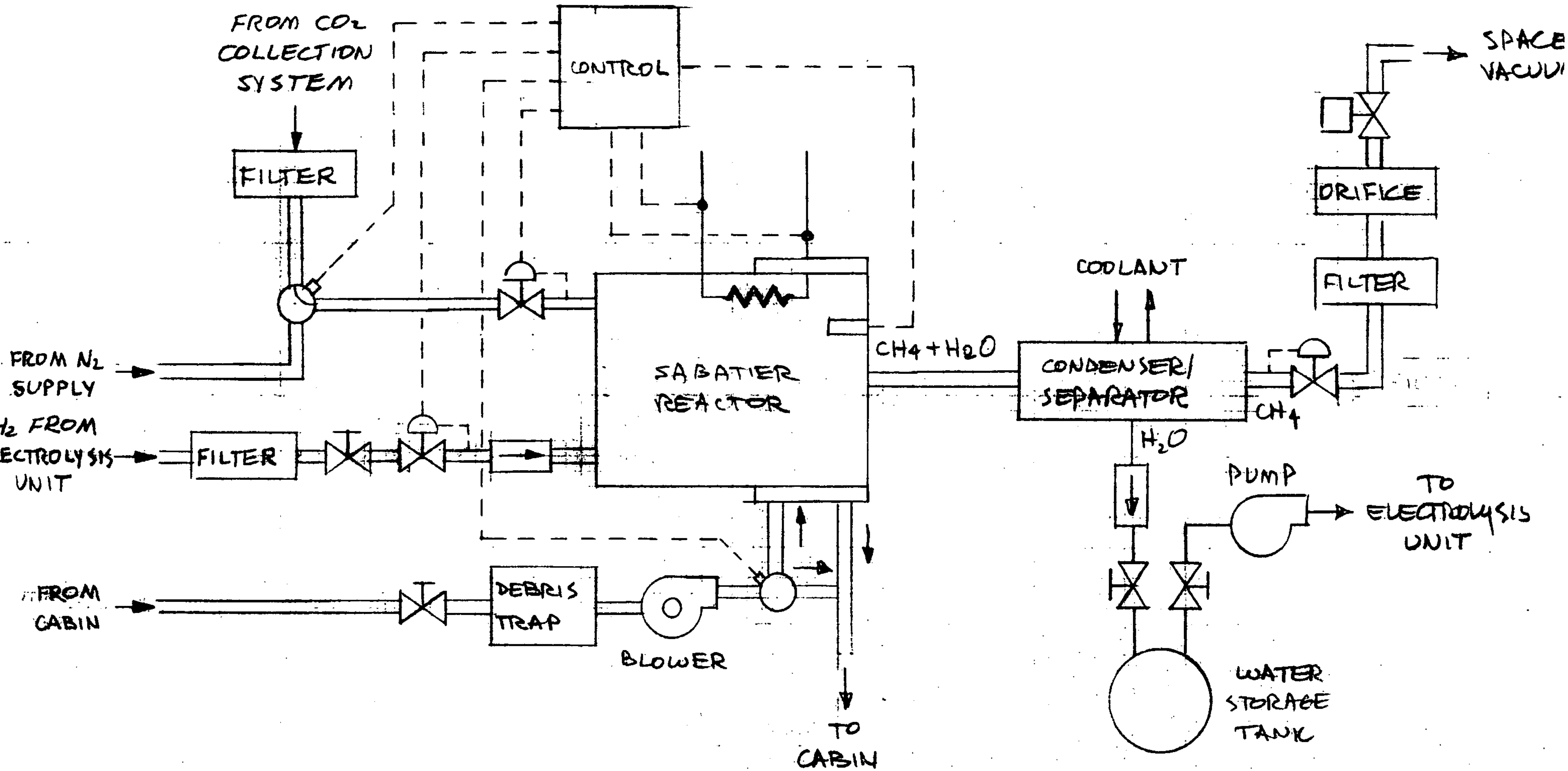

FIGURE 2. SABATIER CO_2 REDUCTION SYSTEM

Cooling air flows through the outer jacket of the reactor to remove process heat. The catalyst bed is normally operated at a pressure ranging from 710 to 750 mmHg and a temperature of 500 to 700°F. The H_2/CO_2 mixture reacts to form methane and steam. The stoichiometric ratio is 4:1 by volume but operation at a ratio of 2.5:1 has been used since it normally eliminates the need of supplying additional hydrogen to the system.

The product gases containing some excess CO_2 and a small amount of unreacted H_2 leave the reactor and flow through the zero-g condenser/separator where the steam is condensed and separated as water. The CH_4 and unreacted gases then flow through the critical-flow reactor pressure-control valve to space vacuum. The zero-g condenser/separator is approximately 8 in. long by 4 in. wide by 1-1/2 in. high and is divided into two compartments by a partition of porous metal. Water, cooled by an integral circuit, wets one surface of the porous plate. The reaction gases flowing along the opposite surface are cooled and the stream condenses and wets the porous surface. The condensed water is then transferred through the porous plate into the cooling water by capillary action and a controlled pressure difference. Product water flowing through the plate increase the displacement of a negative-pressure device. When fully displaced, a reed switch is magnetically tripped, which introduces compressed CO_2 to displace the water into the water storage tank. The backup condenser collects any water it recovers in a small accumulator. A switch in the accumulator activates a positive displacement pump which also discharges the condensate into the water storage tank.

A listing of the components of the Sabatier CO_2 reduction system, including component weights and spares, is given in Table I.

System Performance and Characteristics:

The physical, performance and interface characteristics of the Sabatier CO_2 reduction system are as follows:

TABLE I - SABATIER CO_2 REDUCTION SYSTEM COMPONENTS LIST

COMPONENTS	QUANTITY	SPARES	UNIT WEIGHT (LBS.)
Valve, 3-Way Electrical, Man. Over	2	1	1.5
Valve, Shut-off, Gas	2	1	1.0
Valve, Vacuum, Shut-off Electrical, Man. Over.	1	1	3.0
Valve, Shut-off, Liquid	2	1	0.8
Pressure Regulator	3	2	1.5
Valve, Check, Gas	1	1	0.7
Valve, Check, Liquid	1	1	0.5
Filter, Debris	4	4	2.0
Heat Exchanger, Condenser	1	0	4.0
Separator, Sabatier H_2O	1	1	6.0
Sensor Temperature, Sabatier Reactor	1	2	0.3
Controller, Sabatier Reactor	1	1	6.0
Reactor, Sabatier	1	1	36.0
Blower, Cooling Air	1	1	2.0
Pump Sabatier Condensate	1	1	2.5
Tank, Water Storage	1	1	40.0

Crew Size	=	6 Men
CO_2 Produced, Average	=	2.2 Lbs/Man-Day
CO_2 Produced, Maximum	=	3.11 Lbs/Man-Day
CO_2 Delivery Purity	=	98%
CO_2 Delivery Pressure to Sabatier System	=	30 - 40 PSIA

Performance Characteristics of the system's major components are as follows:

1. Sabatier Reactor

H_2 Feedrate (max lb/hr)	.136
CO_2 Feedrate (max lb/hr)	1.3
H_2 Conversion Efficiency	0.98
Reactor Temperature (°F)	
maximum	700
minimum	450
Startup Heater Power (watts dc unregulated)	150
Catalyst Material	0.5% Ru or Nickel on Alumina
Catalyst Weight (lbs)	15.0
Maximum Operating Pressure (psia)	50
Nominal Operating Pressure (psia)	14
Coolant Air Mass Flowrate (lbs/hr)	60

2. Sabatier Condenser

	Cont	Cycle
Product Gas Flowrate (lb/hr) Nominal	0.63	1.08
Maximum	0.83	1.44
Q Sensible (Btu/hr)	117	200
Q Latent (Btu/hr)	351	604
Gas Outlet Dewpoint (°F)	55	
Gas Side ΔP (in of H_2O)	2.0	
Coolant Inlet Temperature (°F)	50	
Coolant Flowrate (lb/hr)	150	
Coolant Side ΔP (psid)	0.1	

3. Water Separator

Water Flow (max lb/hr)	0.604
Water Removal Efficiency	100%
Maximum Operating Pressure (psia)	50
Nominal Operating Pressure (psia)	14.7

The Sabatier CO_2 reduction system has the following power requirements:

Continuous Power (including cooling air blower), A. C.	85 watts
Heater Start-up Power, D. C., unregulated	150 watts
System's Total Weight	80 Lbs
System's Volume	3 ft^3

Cost Estimating Relationships:

The Sabatier CO_2 reduction system components have been grouped in six groups, designated as I through VI, as shown in the system schematic, Figure 2. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior years dollar values.

Recurring CER's:

1. Sabatier Reactor:

The CER for the Sabatier reactor is given as follows:

Sabatier Reactor Assembly Fabrication Cost $C = 159\, W^{0.267}\, N_p^{1.905}$

$+ \; 3900\, W_{oc}$ dollars

where,

W = Sabatier Reactor Weight = 36 lbs

N_p = Number of ports in reactor = 5, and

W_{oc} = Weight of associated components = 9.7 lbs

Substituting the values of variables in the CER yields:

$$C = 155 \times 2.608 \times 21.5 + 3900 \times 9.7 = 46{,}518 \text{ dollars}$$

2. Cooling Air Blower:

The CER for the cooling air blower fabrication cost is given by $C = 38.2P^{0.942} + 2192\ W_{oc}$ dollars where,

P = electrical power input to the air blower = 50 watts, and
W_{oc} = other components weight = 4.0 lbs.

Substituting the values of the variables in the CER yields:

$$C = 38.2 \times 40 + 2192 \times 4 = 10{,}296 \text{ dollars}$$

3. Condenser and Water Separator:

The following CER is used to evaluate the condenser heat exchanger and separator fabrication costs:

$$C = 159\ w^{0.267}\ N_p^{\ 1.905} + 2959\ W_{oc} \text{ dollars}$$

where

W = condenser heat exchanger weight = 4.0 lbs
N_p = number of ports per heat exchanger = 4, and
W_{oc} = weight of other components = 7 lbs

Subsituting the values of the variable in the CER yields:

$$C = 159 \times 1.45 \times 14.05 + 2959 \times 7 = 23{,}952 \text{ dollars}$$

4. Water Storage Tank:

The CER for the Sabatier water storage tank is given as follows:

Tank fabrication cost $C = 1{,}918\ V^{0.267} + 2959\ W_{oc}$ dollars

where,

V = volume of tank = 1.0 ft^3, and

W_{oc} = weight of associated equipment = 1.5 lbs.

Substituting the above values in the tank's fabrication cost equations results in the following:

$C = 1918 + 2959 \times 1.5 = 6357$ dollars

5. Water Transer Pump:

The CER for the water transfer pump is given by the following relation:

Pump fabrication cost $C = 91\ P_w^{0.942} + 670\ W_{oc}$ dollars

where,

P_w = water transfer pump power input = 20 watts, and

W_{oc} = other components weight = 1.0 lb

Substituting the values of the variables in the above CER yields the following:

$C = 91 \times 16.8 + 670 = 2199$ dollars

6. Controller

The CER used for the controller fabrication cost was based on CER's developed for similar equipment and is given as follows:

Controller fabrication cost $C = 4795\ W$ dollars

where,

W = controller weight = 6.0 lbs

thus,

$C = 4795 \times 6 = 28{,}770$ dollars

Integrated Sabatier CO_2 Reduction System's Recurring CER:

The integration costs of components and assemblies into the Sabatier CO_2 reduction system are obrained by utilizing the system's recurring CER as defined in previous sections of this report. Applying the said CER, then:

$$\text{First unit cost } C_F = 1.833 \times 1.1 \times (46{,}518 + 10{,}296 + 23{,}952 + 6357 + 2199 + 28{,}770) = 2.016 \times 118{,}092 = 238{,}073 \text{ dollars}$$

and assuming the production of two flight-type units, one for flight and the other for back-up, then the total hardware cost is givey by:

$$C_T = 238{,}073 \times (2)^{1-0.1047} = 441{,}625 \text{ dollars}$$

Integrated Sabatier CO_2 Reduction System's Non-Recurring CER's:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on the cost breakdown ratios utilized in the case of the molecular sieves system which have been based on actual cost data collected in NAS9-9018 study. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation:

$$\text{System design cost } C = 34{,}935N + 102{,}942 \text{ dollars}$$

The Sabatier CO_2 reduction system comprises 16 component types as shown in Table I. Accordingly, system design cost C = 558,960 + 102,942 = 661,902 dollars. Values of other non-recurring cost items are listed in Table II, which also shows the breakdown of recurring cost items based on the production of two flight hardware units. All cost figures are in estimated January 1972 dollars.

4.2 BOSCH CARBON DIOXIDE REDUCTION SYSTEM

Process Description:

The Bosch reaction is summarized by the following equation:

$$CO_2 + 2H_2 \rightarrow C + 2H_2O + \text{Heat}$$

TABLE II - SABATIER CO_2 REDUCTION SYSTEM COST BREAKDOWN

Non Recurring		Recurring	
System Engineering Design	661,902	Flight Hardware Production (2 units)	240,951
Subcontractor General and Administrative	342,203	Subcontractor G&A	40,718
Subcontractor Fee	143,633	Subcontractor Fee	17,135
Program Management	49,643	Program Management	6,006
System Engineering	208,499	Sustaining Engineering	8,656
Developmrnt Test	136352		
Qualification Test	100,609		
Reliability Test	162,166		
AGE	732,063		
Tooling	153,561	Sustaining Tooling	7,463
Non-accountable Test Hardware	66,190		
Specifications, Vendor Coordination and Procurement Expense	540,774	Specifications, Vendor Coordination and Procurement Expense	68,408
System Integration	331,613	System Integration	31,576
Prime's Testing	324,332		
Minor Subcontracts	15,224	Minor Subcontracts	20,712
Total	3,968,764		441,625

Total Sabatier CO_2 Reduction System Cost = 3,968,764 + 441,625
= 4,410,389 Dollars

The reaction occurs in the presence of an iron catalyst at temperatures of 1100 to 1800°F. The reaction results in a partial conversion, ranging from 30% at the lower temperatures up to 98% at the higher temperatures. Bosch reactors are usually operated at temperatures between 1100 and 1300°F, where maximum formation of carbon occurs. The reaction gases are recycled to achieve a higher degree of conversion. The reaction rate is controlled by many apparently independent, but nonetheless interrelated variables. The most important variables relate to the conditions in the reactor. These variables may be grouped as the catalyst, the gas stream composition and the reaction kinetics. Reaction kinetics include the effect of reactor temperature and the gas flow rate or recycle rate through the reaction loop as controlled by the recycle compressor. Increasing the flow rate through the reactor increases the probable number of collisions per unit time, thereby increasing the reaction rate, and this in turn calls for higher compressor power requirements.

Conversion rates were found to be somewhat insensitive to reactant gas H_2 to CO_2 volume ratio, but were more favorable when a hydrogen-rich ratio was employed. Two types of Bosch units have been used in practice. The first utilizes expendable cartridge catalysts. The other type employes a nonexpendable rotating catalyst. A schematic diagram of a Bosch CO_2 Reducer with an expendable cartridge catalyst is shown in Figure 3. A compressor is used to circulate carbon dioxide, makeup hydrogen, and recycle gases through the system. The gases are heated in a regenerative heat exchanger by the hot exit gases from the reactor before entering the reactor. The reactor is basically a canister with startup strap heaters wound around its external circumference. The expendable cartridge is a screen mesh cylinder filled with the steel wool catalyst and placed inside the reactor housing. A filter is placed downstream of the reactor to trap solid carbon or other particles. The resultant water is condensed in the condenser/H_2O separator, collected, and piped to the water electrolysis unit.

A listing of the components of the Bosch CO_2 reduction system including component weights and spares, is given in Table III.

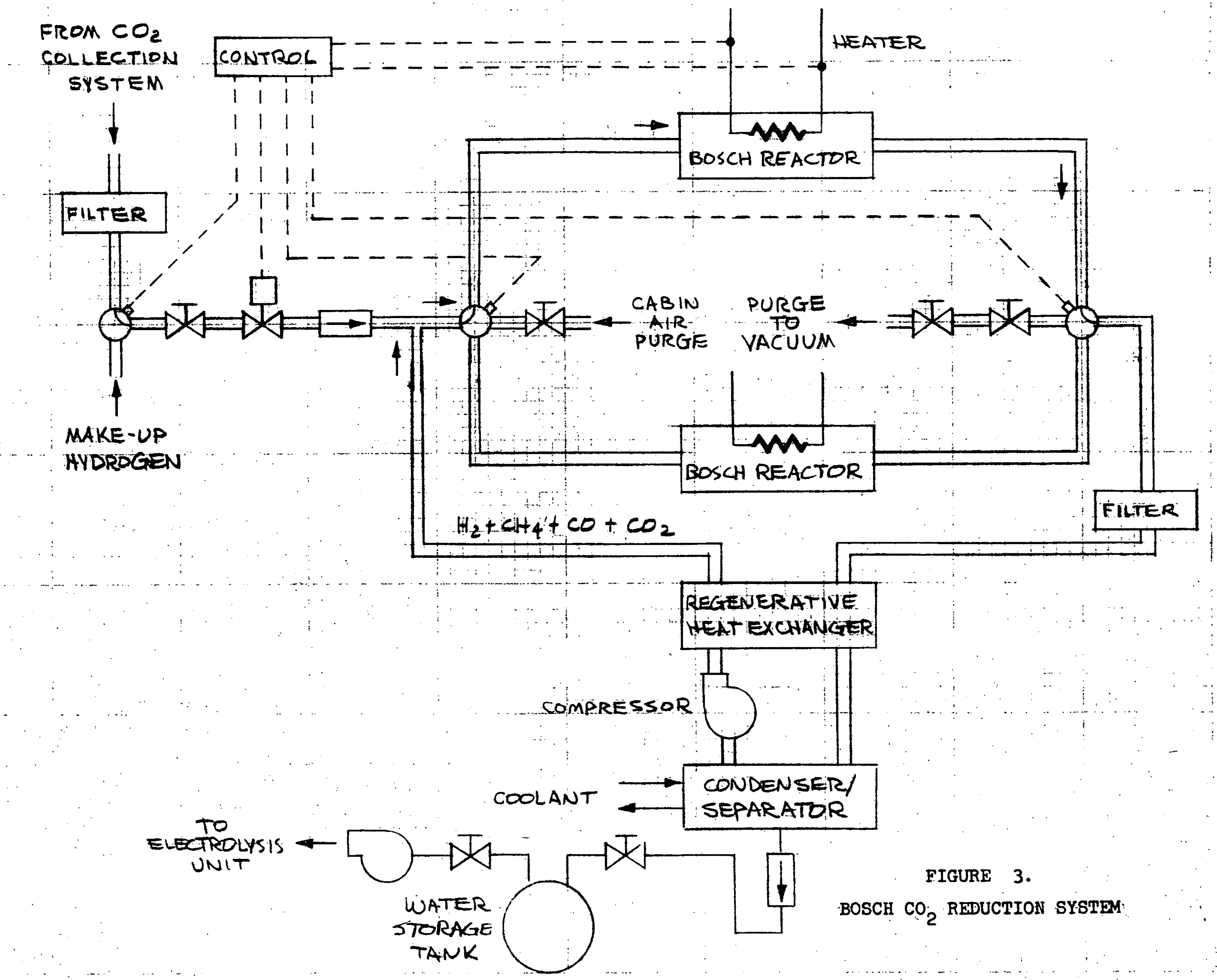

FIGURE 3.

BOSCH CO_2 REDUCTION SYSTEM

TABLE III BOSCH CO_2 REDUCTION SYSTEM COMPONENTS LIST

COMPONENT	QUANTITY	SPARES	UNIT WEIGHT (LBS.)
Valve, 3-Way Electrical Man. Over	1	1	2.5
Valve, 4-Way Electrical, Man. Over	2	1	2.5
Valve, Shut-off, Gas	3	2	1.0
Valve, Vacuum, Shut-off, Electrical, Man. Over.	1	1	3.0
Valve, Shut-off, Liquid	2	1	0.8
Valve, Shut-off, Elect., Man. Over	1	1	2.0
Valve, Check, Gas	1	1	0.7
Valve, Check, Liquid	1	1	0.5
Tank, water storage	1	1	40.0
Filter, Debris	2	2	2.0
Heat Exchanger, Regenerative	1	0	10.0
Heat Exchanger Condenser	1	0	4.0
Separator, Water	1	1	6.0
Controller, Bosch Reactor	1	1	6.0
Reactor, Bosch	1	1	25.0
Compressor, Recycle Gases	1	1	2.0
Pump, Condensate	1	1	2.5

System Performance and Characteristics:

The physical, performance and interface characteristics of the Bosch CO_2 Reduction System are as follows:

Capacity, number of men	6
CO_2 rate, lb/man-day, average	2.2
Feed gas impurities, maximum % by volume	1.0
Feed gas pressure range, psig	5 to 10
Recycle flow rate lb/day	144
Catalyst cartridge replacement interval, days	3
Condenser coolant	Water
Coolant inlet temperature, ^{o}F	40
Coolant flow, lb/hr	90
Ambient temperature, ^{o}F	75
Ambient pressure, psia	14.7
Reduction unit pressures, psia	> 14.7
Maximum reactor pressure, psig	15.0
Dry recycle gas composition, % by volume	
H_2	40
CH_4	30
CO	20
CO_2	10
Water production rate, lbs/day	10.8
Hydrogen flow rate, lbs/day	1.2
Carbon Production rate lbs/day	3.6
System's power requirement:	
Compressor, continuous, watts	450
Instrumentation, continuous, watts	20
Heater, start-up only, watts	500
Systems total weight, lbs.	120
System's volume, Ft^3	4.5

Cost Estimating Relationships:

Bosch CO_2 reduction system components have been grouped in seven groups, designated as I through VII, as shown in the system schematic, Figure 3. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior years dollar values.

Recurring CER"S:

1. Bosch Reactor:

   The CER for the Bosch reactor was assumed to be similar to that used for the Sabatier reactor and is given as follows:

   Bosch reactor assembly fabrication cost C

   $$= 159\, W^{0.267} N_p^{1.905} Q^{0.89} + 3900\, W_{oc} \qquad \text{dollars}$$

   where,

W	= Sabatier Reactor Weight	= 25 lbs.,
N_p	= Equivalent number of ports in reactor	= 2
Q	= Number of reactors	= 2, and
W_{oc}	= Weight of Associated Components	= 11.7 lbs

   Note that the reactor has only one port, but due to its complexity, it was assumed to be equivalent to 2 ports. Substituting the values of variables in the CER yields:

   $$C = 155 \times 2.366 \times 3.93 \times 1.855 + 3900 \times 11.7 = 48{,}304 \text{ dollars}$$

2. Recycle Gases Compressor:

   The recycle gases compressor CER is given by the following:

   Compressor Fabrication Cost $C = 38.2\, P^{0.942}$ dollars,

   where,

P = electrical power input to the compressor = 200 watts, and

Substituting the value of the variable P in the CER yields: $C = 5654$ dollars

3. Condenser/Separator

The CER for the condenser/separator utilizes the heat exchanger relation for the condenser and assumes the separator to be part of the associated components, W_{OC}. The condenser/separator fabrication cost equation is given as follows:

$$C = 159W^{0.267}N_p^{1.905} + 2959\ W_{OC} \text{ dollars}$$

where,

W = Condenser heat exchanger weight = 4.0 lbs.

N_p = number of ports per heat exchanger = 4, and

W_{oc} = weight of other components = 0.5 lbs.

Substituting the values of the variable in the CER yields:

$$C = 159 \times 1.45 \times 14.05 + 2959 \times 0.5 = 4{,}719 \text{ dollars}$$

4. Water Storage Tank:

The CER for the condensate water storage tank is given as follows:

$$\text{Tank fabrication cost } C = 1{,}918\ V^{0.267} + 2959\ W_{oc} \text{ dollars}$$

where,

V = volume of tank = 1.0 FT^3, and

W_{oc} = weight of associated equipment = 1.0 lbs.

Substituting the above values in the tank's fabrication cost equations result in the following:

$$C = 1918 + 2959 \times 1.0 = 4877 \text{ dollars}$$

5. Water Transfer Pump:

The CER for the water transfer pump is given by the following relation:

$$\text{Pump fabrication cost } C = 91\ P_w^{0.942} + 670\ W_{oc} \quad \text{dollars}$$

where,

P_w = water transfer pump power input = 20 watts and

W_{oc} = other components weight = 1.0 lb.

Substituting the values of the variables in the above CER yields the following:

$$C = 91 \times 16.8 + 670 = 2199 \quad \text{dollars}$$

6. Regenerative Heat Exchanger:

The recycle gas loop regenerative heat exchanger CER is given by the following:

$$\text{Heat exchanger fabrication cost } C = 159\ W^{0.267} N_P\ 1.905 + 2959\ W_{OC} \text{ dollars}$$

where,

W = heat exchanger weight = 10.0 lbs,

N_P = number of ports per heat exchanger = 4,

W_{OC} = weight of other components = 8.5 lbs

Substituting the values of the variable in the CER yields:

$$C = 159 \times 1.85 \times 14.05 + 2959 \times 8.5 = 29{,}285$$

7. Controller

The CER used for the controller fabrication cost was based on CER's developed for similar equipment and is given as follows:

$$\text{Controller fabrication cost } C = 4795\ W \quad \text{dollars}$$

where,

W = controller weight = 6.0 lbs

thus,

$$C = 4795 \times 6 = 28{,}770 \quad \text{dollars}$$

Integrated Bosch System's Recurring CER:

The integration costs of components and assemblies into the Bosch CO_2 reduction system are obtained by utilizing the system's recurring CER as defined in previous sections of this report. Applying the said CER, then:

First unit cost $C_F = 1.833 \times 1.1 \times (48{,}304 + 5{,}654 + 4{,}719 + 4{,}877$

$+ 2{,}199 + 29{,}285 + 28{,}770)$

$= 2.0163 \times 123{,}808 = 249{,}634$ dollars

and assuming the production of two flight-type units, one for flight and the other back-up, then the total hardware cost is given by:

$$C_T = 249{,}634 \times (2)^{1-0.1047} = 463{,}071 \quad \text{dollars}$$

Integrated Bosch CO_2 Reduction System's Non Recurring CER's:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on the cost breakdown ratios utilized in the case of the molecular sieves system which have been based on actual cost data collected in NAS9-9018 study. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation:

System design cost $C = 34{,}935N + 102{,}942$ dollars

The Bosch CO_2 Reduction System comprises 17 component types as shown in Table III. Accordingly, system design cost $C = 593{,}895 + 102{,}942 = 696{,}837$ dollars

Values of other non-recurring cost items are listed in Table IV, which also shows the breakdown of recurring cost items based on the production of two flight hardware units. All cost figures are in estimated January 1972 dollars.

4.3 SOLID POLYMER ELECTROLYTE (SPE) ELECTROLYSIS SYSTEM:

The SPE electrolysis system comprises the electrolysis modules, pumps deidnizer columns, filters, heat exchangers gas/liquid separators pressure regulators, valves and associated components. A schematic of the SPE electrolysis system is shown in Figure 4. The system operation is as follows: The make-up water is mixed with the recycled cooling water upstream of the water pump filters. The process water rate is fixed and pumped by the water metering pump. Downstream of the pump, the water flows through two process water deionizer resin beds which

TABLE IV - BOSCH CO_2 REDUCTION SYSTEM COST BREAKDOWN

Non-Recurring		Recurring	
System Engineering Design	696,837	Flight Hardware Production (2 units)	252,651
Subcontractor General and Administrative	360,265	Subcontractor G&A	42,695
Subcontractor Fee	151,214	Subcontractor Fee	17,967
Program Management	52,263	Program Management	6,298
System Engineering	219,504	Sustaining Engineering	9,076
Development Test	143,548		
Qualification Test	105,919		
Reliability Test	170,725		
AGE	770,702		
Tooling	161,666	Sustaining Tooling	7,826
Non-accountable Test Hardware	69,684		
Specifications, Vendor Coordination and Procurement Expense	569,316	Specifications, Vendor Coordination and Procurement Expense	71,730
System Integration	349,115	System Integration	33,110
Prime's Testing	341,450		
Minor Subcontracts	16,027	Minor Subcontracts	21,718
Total	4,178,235		463,071

Total Bosch CO_2 Reduction System Cost = 4,178,235 + 463,071
= 4,641,306 dollars

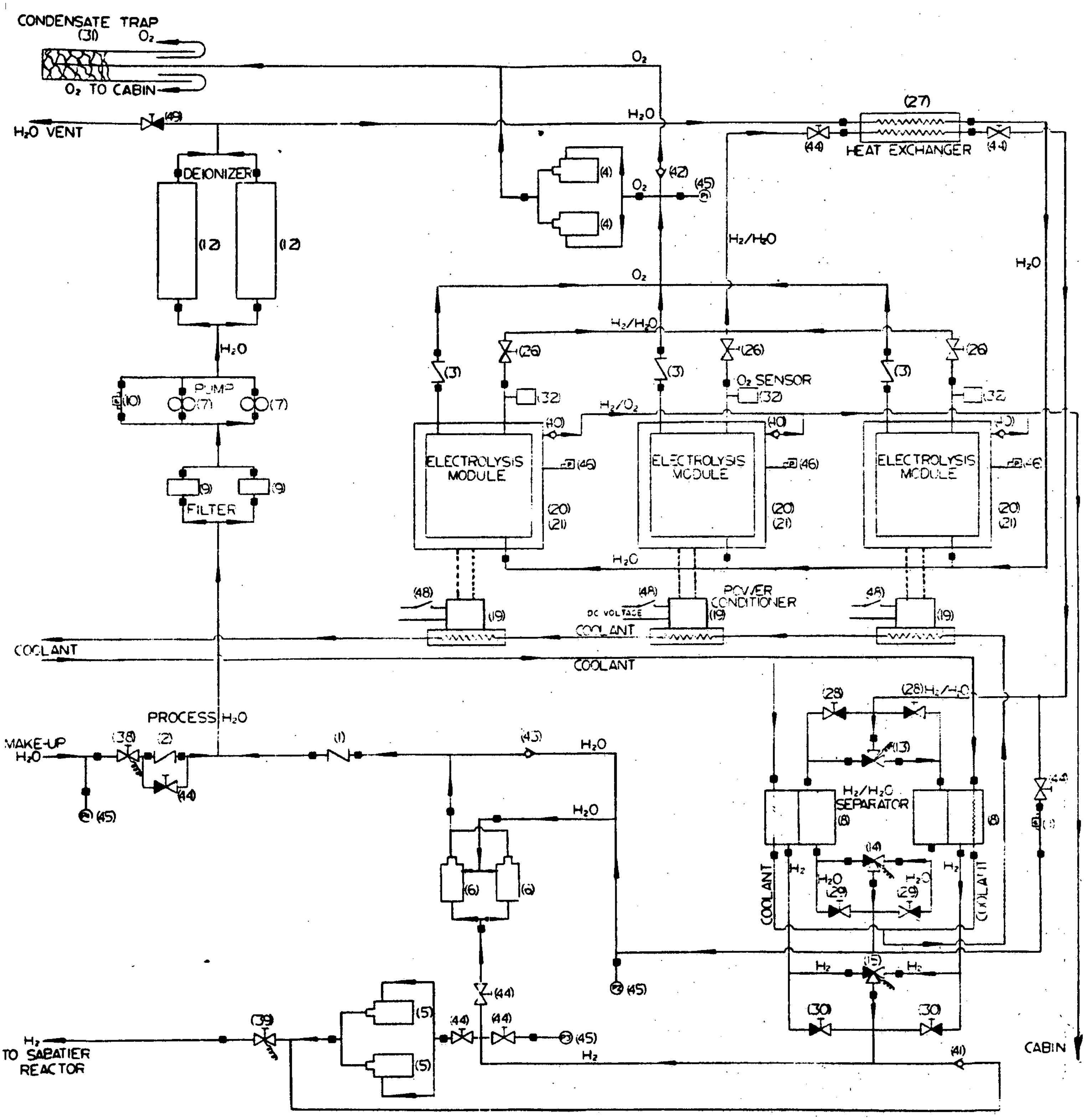

FIGURE 4 - SOLID POLYMER ELECTROLYTE WATER ELECTROLYSIS SUBSYSTEM SCHEMATIC

reduces the contaminant level to acceptable system limits. The water then passes through a regenerative heat exchanger to increase the water temperature as it enters the electrolysis module for optimum system performance. Each module is packaged within a container which is isolated from space vacuum by the container pressure relief valve.

Since the electrolysis mode of operation is by water feed to the cathode side only, water required for the anode side reaction diffuses through the cell electrolyte to generate oxygen at a rate determined by cell current. The generated oxygen thus contains only saturated water vapor at the temperature and pressure level of the oxygen exit side. The generated hydrogen contains the free liquid water required for module temperature control with this gas/water mixture subsequently passing through the normally-open manual module isolation valve. The oxygen sensor installed on the hydrogen discharge side senses the presence of oxygen in the hydrogen stream in the event of an internal cell leak and automatically removes power to the failed module. The hydrogen/water mixture passes through one side of the regenerative heat exchanger to transfer heat to the incoming process feed water. This mixture then enters into the H_2/H_2O phase separator. The exit water from the separator then passes to H_2/H_2O differential back-pressure regulators. The exit hydrogen from the separator similarly passes to a pair of H_2 absolute back-pressure regulators. The H_2/H_2O differential back-pressure regulators are referenced to the exit H_2 pressure.

No phase separation is required on the oxygen discharge side of the module due to expansion of the oxygen/water vapor mixture from a high module pressure of about 65 psia to the delivery cabin pressure of 5-14.7 psia. This lowers the dew point, resulting in no water condensation occurring in the oxygen discharge stream during normal operation. A condensate trap is installed on the system oxygen outlet to the cabin to collect any small amount of condensate accumulated during system shutdown or transients. Sustained operation then evaporates this residue. This water condensate is ultimately removed to the cabin environment by evaporation. The oxygen is delivered directly to the cabin through the O_2 absolute back-pressure regulator.

The spacecraft Liquid Heat Transport Loop provides water coolant to the hydrogen side phase separator and power conditioners for removal of most of the heat generated during the electrolysis cycle. The remainder of the heat is rejected to the cabin environment from the system package. No active temperature controls are required in the system throughout its operating range. A listing of the components of the SPE water electrolysis system, including component weights and spares, is given in Table V.

System Performance and Characteristics:

The physical, performance and interface characteristics of the SPE electrolysis system are as follows:

Capacity, number of men	6
O_2 Consumption rate, metabolic, Lbs/Man-day	2.0
O_2 Leak rate, lbs/day	2.0
Cabin total pressure, psia	5.0 to 14.7
Cabin oxygen partial pressure, psia	3.1
Cabin nitrogen partial pressure	Diluent
Hydrogen supply rate, Lbs./day	1.56
Oxygen outlet pressure range, psia	0 to 14.7
Hydrogen outlet pressure range, psia	0 to 40
Maximum coolant inlet temperature, ^{o}F	50
Cabin temperature range, ^{o}F	63 to 77
Feed water inlet temperature range, ^{o}F	50 to 160
Cabin dewpoint range	46 to 60
Coolant medium	water
Coolant flow rate, Lbs/Hr	60
Input water electrolysis voltage range, VDC	40 to 60
Input instrumentation voltage range, VDC	25 to 31
Nominal input power (3 modules operating, including power conditioning), watts	1420
Instrumentation/control input power, watts	20
Maximum heat rejection to cabin air, BTU/Hr	125
Maximum Heat rejection to coolant loop, BTU/Hr	678
Installed system weight, Lbs.	140

TABLE V- SPE ELECTROLYSIS SYSTEM COMPONENT LIST

COMPONENT	QUANTITY	SPARES	COMPONENT WEIGHT (LBS.)
Back-Pressure Regulator, ABS	4	4	2.50
Pressure Regulator, Differential	2	2	2.50
Valve, Solenoid, Gas	3	2	1.00
Valve, Solenoid, Liquid	2	1	1.00
Valve, ABS. Relief, Gas	4	1	1.50
Valve, ABS. Relief, Liquid	1	0	1.50
Valve, Check, Gas	4	8	0.70
Valve, Check, Liquid	1	2	0.50
Valve, Shut-off, Manual, Gas	7	3	0.75
Valve, shut-off, manual, liquid	2	1	0.75
Valve, manual vent, water	1	0	0.75
Electrolysis Module	3	2	16.50
Pump, Metering	2	2	2.25
Condenser/Separator	2	1	5.00
Filter, Water	2	10	1.50
Pressure Switch	3	1	0.60
Pressure Switch, Differential	2	4	0.60
Deionizer, Water	2	10	16.00
Valve, Quick Disconnect,Gas	30	3	0.50
Valve, Quick Disconnect, Liquid	38	5	0.50
Heat Exchanger	1	1	4.00
Power Conditioner	3	1	10.00
Coldplate	3	1	4.00
Condensate Trap	1	0	0.50
Oxygen Sensor	3	1	1.20
Control Electronics	1	1	3.00
Gage, Pressure Readout	4	4	0.25

Cost Estimating Relationships:

The SPE Electronics System components have been grouped in six groups, designated as I through VI, as shown in Figure 4. The recurring and non-recurring CER'S presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER'S developed and based on prior year dollar values.

Recurring CER'S:

1. Electrolysis modules

A study of the costs of similar electrochemical cells and of prototype water electrolysis cells indicates that the SPE electrolysis module fabrication cost may be given by the following relation:

$$C = (6250\ W_M + 2192\ W_{oc} + 2000\ )Q^{0.89} \quad \text{dollars}$$

where,

W_M = Weight of module = 16.5 lbs.,

Q = number of modules = 3 , and

W_{oc} = weight of associated components = 7.0 lbs.

Substituting the values of the variables in the above CER yields the following:

$$C = (2650 \times 16.5 + 2192 \times 7 + 2000) \times 2.66$$
$$= (103,125 + 15,344 + 2000) \times 2.66 = 324,645 \quad \text{dollars}$$

2. Pumps:

The CER for the water metering pump assembly is given by the following relation:

Condensate Pump and Condensate Loop Fabrication Cost C

$$= 91\ P_W^{0.942}\ Q^{0.89} + 670\ W_{OC} \text{ dollars}$$

where,

P_W = condensate pump power input = 20 watts,

Q = number of pumps = 2, and

W_{OC} = other components weight = 23.5 lbs

Substituting the values of the above variables in the pumps fabrication cost equation results in the following:

$$C = 91 \times 16.8 \times 1.855 + 670 \times 23.5 = 18{,}580 \quad \text{dollars}$$

3. Deionizers:

The CER utilized for the Deionizers is similar to that used for cost estimating multifiltration units and is given by the following:

Deionizers fabrication cost $C = 200\ W_D\ Q^{0.89} + 670\ W_{OC}$ dollars

where,

W_D = deionizer weight = 16 lbs.,

Q = number of deionizer units = 2, and

W_{oc} = weight of associated components = 2 lbs.

Substituting the values of variables in the above CER yields:

$$C = 200 \times 16 \times 1.855 + 2 \times 670 = 7276 \quad \text{dollars}$$

4. Heat Exchanger:

The CER for H_2/H_2O to water vapor heat exchanger is given by the following:

Heat exchanger assembly fabrication cost $C = 159W^{0.267}N_p^{1.905} + 2959\ W_{OC}$ dollars

where,

W = heat exchanger weight = 4.0 lbs,

N_p = number of ports per chiller = 4, and

W_{OC} = weight of associated components = 12.5 lbs

Substituting the values of variables in the CER yields:

$$C = 159 \times 1.45 \times 14.05 + 2959 \times 12.5 = 40{,}227 \text{ dollars}$$

5. Power Conditioner/Coldplate Assembly:

The CER's for the power conditioner/coldplate assemblies include terms for both the power conditioner and the heat exchanger coldplate. The power conditioner/coldplate assembly fabrication cost is given by the following relation:

$$C = (14.9P^{0.942} + 1414\ (W)^{0.267} N_p^{1.905}) \times Q^{0.89} \quad \text{dollars}$$

where,

P = power conditioner's power requirement = 1000 watts,

W = weight of coldplate = 4.00 lbs.,

N_p = number of ports per coldplate = 2, and,

Q = number of conditioner/coldplate assemblies = 3.

Substituting the values of variables in the above CER yields the following:

$$C = (14.9 \times 670 + 1414 \times 1.45 \times 3.72) \times 2.56 = 45{,}080 \text{ dollars}$$

6. Condenser/Separator Assembly:

The assembly contains hydrophilic porous glass tubes which pass water and hydrophobic teflon membranes which pass hydrogen, integrated with the heat exchanger which picks up the heat rejected from the hydrogen/water mixture. The CER used for the fabrication cost of the condenser/hydrogen separator assembly is given as follows:

$$C = 159\ W^{0.267}\ N_p^{1.905}\ Q^{0.89} + 2959\ W_{oc} \quad \text{dollars}$$

where,

W = heat exchanger weight = 5.00 lbs.

N_p = number of ports per heat exchanger assembly = 5,

Q = number of heat exchanger assemblies = 2, and

W_{oc} = weight of associated components = 27.0 lbs.

Substituting the values of the variables in the above CER yields the following

$$C = 159 \times 1.54 \times 21.4 \times 1.855 + 2959 \times 27 = 89{,}610 \text{ dollars}$$

Integrated SPE Electrolysis System's Recurring CER:

The integration costs of components and assemblies into the SPE water electrolysis system are obtained by utilizing the system's recurring CER as defined in previous sections of the report. Applying the said CER, then

$$\text{First unit cost } C_F = 1.833 \times 1.1 \times (324{,}645 + 18{,}580 + 7{,}276 + 40{,}227 + 45{,}080) = 1{,}095{,}700 \text{ dollars}$$

and assuming the production of two flight-type units, one for flight and the other for back-up, then the total hardware recurring cost is given by:

$$C_T = 1{,}095{,}700 \times (2)^{1-0.1047} = 2{,}032{,}500 \text{ dollars}$$

Integrated SPE Water Electrolysis System's Non-Recurring CER's:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on the cost breakdown ratios utilized in the case of the molecular sieves system which have been based on actual cost data collected in NAS9-9018 study. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation.

$$\text{System design cost } C = 34{,}935N + 102{,}942 \text{ dollars}$$

The SPE water electrolysis system comprises 27 component types as shown in Table V. Accordingly, system design cost C = 943,245 + 102,942 = 1,046,187 dollars.

Values of other non-recurring cost items are listed in Table VI which also shows the breakdown of recurring cost items based on the production of two flight hardware units. All cost figures are in estimated January 1972 dollars.

TABLE VI - SPE WATER ELECTROLYSIS SYSTEM COST BREAKDOWN

Non-Recurring		Recurring	
System Engineering Design	1,046,187	Flight Hardware Production (2 units)	1,108,932
Subcontractor General and Administrative	540,879	Subcontractor G&A	187,397
Subcontractor Fee	227,023	Subcontractor Fee	78,861
Program Management	78,464	Program Management	27,642
System Engineering	329,549	Sustaining Engineering	39,837
Development Test	215,515		
Qualification Test	159,020		
Reliability Test	256,316		
AGE	1,157,082		
Tooling	242,715	Sustaining Tooling	34,349
Non-accountable Test Hardware	104,619		
Specifications, Vendor Coordination and Procurement Expense	854,735	Specifications, Vendor Coordination and Procurement Expense	314,834
System Integration	524,140	System Integration	145,324
Prime's Testing	512,632		
Minor Subcontracts	24,062	Minor Subcontracts	95,324
Total	6,272,938		2,032,500

Total SPE water Electrolysis System Cost = 6,272,938 + 2,032,500

= 8,305,438 dollars

4.4 CIRCULATING KOH ELECTROLYTE WATER ELECTROLYSIS SYSTEM:

This type of electrolysis cells uses a potassium hydroxide electrolyte, as a solution of 35% KOH in water, which is contained in an asbestos matrix held between two electrodes The alkaline electrolyte is circulated between the dual asbestos matrix of the cell and is cooled by a heat exchanger external to the cell. The circulation of the electrolyte helps to minimize concentration polarization and decrease the time required to reach steady-state operation after either starting up or adding make-up water to the electrolyte. A schematic ofthe circulating KOH electrolysis system is shown in Figure 5. The system comprises three electrolysis modules. Each contains 16 cells, connected hydraulically in parallel and divided electrically into two eight-cellbanks. Cells within an eight-cell electrical bank are connected in series. Peripheral manifolding within the module provides separate paths for electrolyte circulation oxygen and hydrogen discharge, and nitrogen purge. By differential p pressure control, the gas-liquid interface in the absorbent matrices contiguous to the electrodes is maintained to achieve phase separation. The electrolyte is pumped through a closed circulation loop by using one of two-in-line magnetic-coupled centrigufal pumps. The electrolyte leaving the pump passes through the tube side of a shell-and-tube heat exchanger. Coolant supplied to the shell side removes waste heat generated in the electrolysis modules. The electrolyte flow is split at a set of flowmeters into three paths leading to the electrolysis modules. Flow control valves in these lines are used to balance the flowmeters. Downstream of the electrolysis modules, the electrolyte is manifolded together and enters the electrolyte reservoir to be returned to the pump. Reference pressure is utilized from an external nitrogen pressure source controlled to the desired system pressure.

Water feed for the elecrrolysis process is supplied by direct injection into the reservoir. The proper water pressure and flow rate are effected by means of a gear pump, a manually adjustable flow control valve, and solenoid valve.

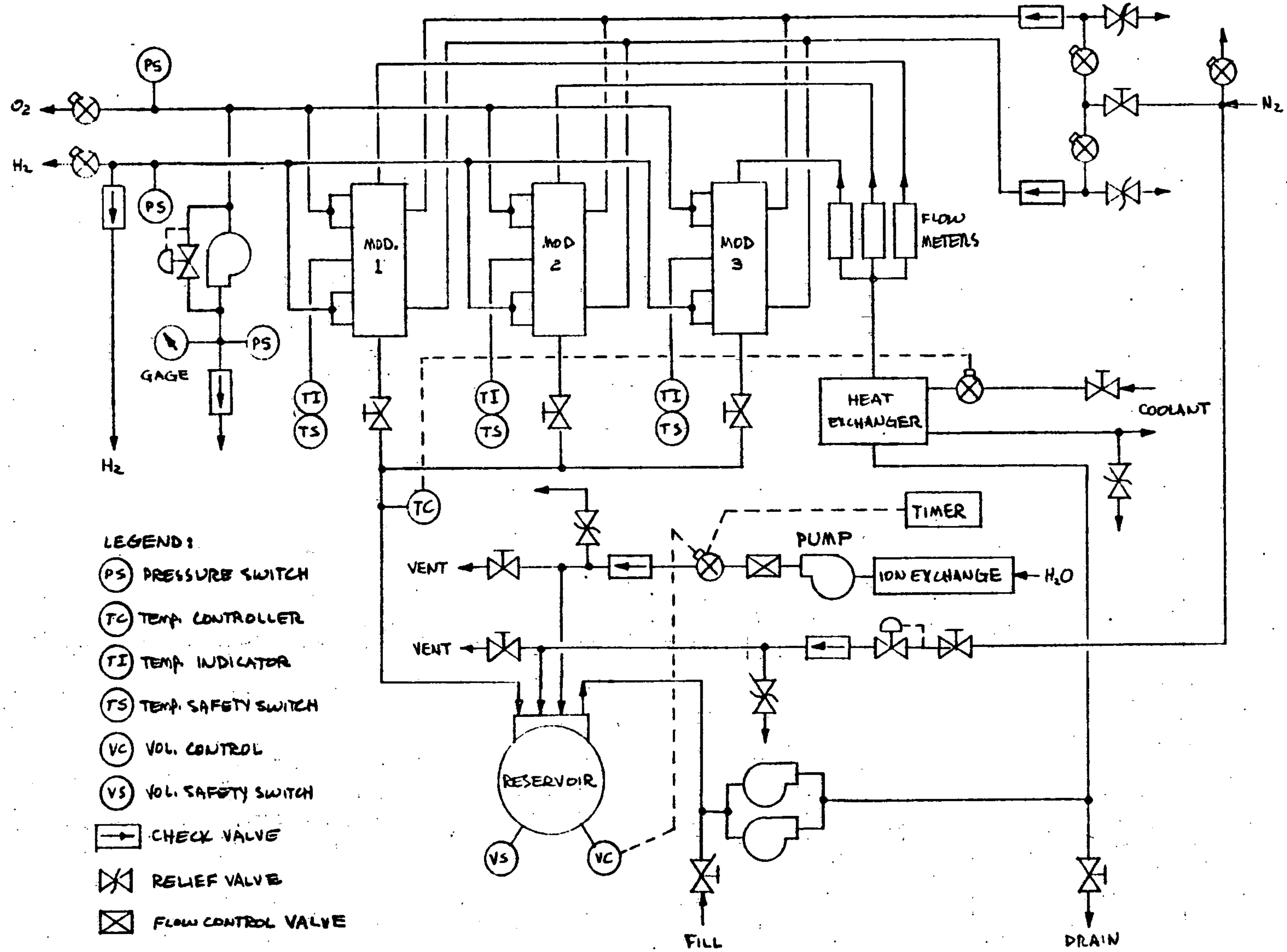

FIGURE 5. CIRCULATING KOH ELECTROLYTE SUBSYSTEM SCHEMATIC

Hydrogen is delivered from the electrolysis modules at approximately 9 psig. Oxygen discharged from the electrolysis modules at approximately 9 psig is pumped to 21-27 psig by means of a diaphragm pump. A pressure regulator across the pump maintains the pump suction pressure at 5 psig. Nitrogen purge is provided to maintain gas-liquid differential pressure during startup and interim shutdown. When this function is actuated, whether manually or automatically during safety shutdown, inlet and outlet solenoid valves in the hydrogen and oxygen discharge lines open, allowing nitrogen to flow through the oxygen and hydrogen chambers of the electrolysis modules. A micrometer valve is used to adjust the nitrogen flow rate. A listing of the components of the circulating KOH electrolysis system, including component weights and spares, is shown in Table VII.

<u>System Performance and Characteristics:</u>

The physical, performance and interface characteristics of the circulating KOH electrolysis system are as follows:

capacity, number of men	6
O_2 Consumption rate, metabolic, lbs./man-day	2.0
O_2 Leak rate, lbs./day	2.0
Cabin total pressure psia	5.0 to 14.7
Cabin oxygen partial pressure, psia	3.1
Cabin nitrogen partial pressure	Diluent
Nominal cell voltage	1.8 to 2.1
Hydrogen supply rate, lbs./day	1.56
Oxygen outlet pressure range, psia	21 to 27
Hydrogen outlet pressure range, psig	9
Maximum coolant temperature, ^{o}F	55
Cabin temperature range ^{o}F	63 to 77
Feed water inlet temperature range, ^{o}F	50 to 160
Cabin dewpoint range	46 to 60
Coolant medium	Water
Coolant flow rate, GPM	0.5

System Power Requirements:

45 ma	120/208 VAC, 400 Hz (3 sec. on, 15 min. off)
4.0 amp	115 vac, 1 phase, 60 Hz for controls and the oxygen compressor
1950 watts	DC on high mode operation, continuous
670 watts	DC on low mode operation, 2 hours/day

Installed System weight, lbs. 180

Cost Estimating Relationships:

The circulating KOH electrolysis system components have been grouped in five groups, designated as I through V, as shown in Figure 5. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior year dollar values.

Recurring CER'S:

1. Electrolysis modules:

A study of the costs of similar electrochemical cells and of prototype water electrolysis cells indicates that similar to the SPE electrolysis module, the circulating KOH electrolysis module fabrication cost may be given by the following relation:

$$C = (6250\ W_M + 2000)Q^{0.89} + 2192\ W_{oc} \quad \text{dollars}$$

where,

W_M = weight of module = 15 lbs.,

Q = number of modules = 3, and

W_{oc} = weight of associated components = 15.6 lbs.

Substituting the values of the variables in the above CER yields the following:

$$C = (6250 \times 15 + 2000) \times 2.66 + 2192 \times 15.6 = 288{,}890 \quad \text{dollars}$$

2. Compressor:

The CER utilized for oxygen supply compressor assembly is given by the following:

Compressor assembly fabrication cost $C = 38.2\ P_W^{0.942} + 2192\ W_{oc}$ dollars

where,

P_w = compressor power input = 35 watts, and

W_{oc} = other components weight = 8.5 lbs.

Substituting the values of variables in the above CER yields the following:

$C = 38.2 \times 28.5 + 2192 \times 8.5 = 19{,}720$ dollars

3. Reservoir:

The CER utilized for the water reservoir is given as follows:

Reservoir fabrication cost $C = 1918V^{0.267} + 2959\ W_{oc}$ dollars

where,

V = tank volume = 1.0 ft^3, and

$W_{\theta C}$ = Weight of associated components = 1.0 lb.

Substituting the values of the variables in the above CER gives the following:

$C = 1918 + 2959 = 4877$ dollars

4. Heat Exchanger:

The CER for the liquid-to-liquid heat exchanger water cooler is given by the following:

Heat exchanger fabrication cost C'

$= 159\ W^{0.267} N_P^{1.905} + 2959\ W_{OC}$ dollars

where, W = heat exchanger weight = 4.0 lbs.,

N_P = number of ports per heat exchanger = 4,

W_{OC} = weight of other components = 6.25 lbs.

Substituting the values of the variable in the CER yields:

$C = 159 \times 1.45 \times 14.05 + 6.25 \times 2959 = 21{,}733$ dollars

TABLE VII - CIRCULATING KOH ELECTROLYSIS SYSTEM COMPONENT LIST

COMPONENT	QUANTITY	SPARES	COMPONENT WEIGHT (LBS)
Electrolysis Module	3	3	15.00
Valve, Gas Manual	3	2	0.75
Valve, Gas, Solenoid	5	2	1.00
Valve, Relief, Gas	3	2	1.50
Valve, Relief, Liquid	2	1	1.50
Valve, Check, Gas	5	3	0.75
Pressure Regulator	2	2	2.50
Temperature Indicator	3	2	0.20
Temperature Safety Switch	3	2	0.50
Compressor	1	1	3.00
Pressure Switch	3	3	0.50
Gage	1	1	1.00
Reservoir	1	0	50.00
Volume Control	1	1	0.50
Temperature Control	1	1	0.50
Volume Safety Switch	1	1	0.50
Heat Exchanger	1	0	4.00
Flow Meter	3	2	1.00
Pump	3	2	2.50
Timer	1	1	6.00
Valve, Flow Control	1	1	1.00
Valve, Liquid, Manual	7	4	0.75
Valve, Liquid, Solenoid	2	1	1.00
Valve, Liquid, Check	1	1	0.50
Filter, Ion Exchange	1	1*	8.00

(*) NOTE: Plus replacements, as required

5. Pumps:

The CER for the two-water transfer pump assemblies, including the ion exchange filter and timer is given by the following relation:

Condensate Pump and condensate Loop Fabrication Cost C

$$= 91\ P_W^{0.942} Q^{0.89} + 670\ W_{OC} \quad \text{dollars}$$

where,

P_W = condensate pump power input = 20 watts,

Q = number of pumps = 3 and

W_{OC} = other components weight = 19.5 lbs

Substituting the values of the above variables in the pumps fabrication cost equation results in the following:

$$C = 91 \times 16.8 \times 2.66 + 670 \times 19.5 = 17{,}132 \quad \text{dollars}$$

Integrated Circulating KOH Electrolysis System's Recurring CER

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on the cost breakdown ratios utilized in the case of the molecular sieves system which have been based on actual cost data collected in NAS9-9018 study. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation.

System design cost C = 34,935N + 102,942 dollars

The circulating KOH electrolysis system comprises 25 component types as shown in Table VII. Accordingly, system design cost C = 873,375 + 102,942 = 176,317 dollars.

TABLE VIII - CIRCULATING KOH ELECTROLYSIS SYSTEM COST BREAKDOWN

Non-Recurring		Recurring	
System Engineering Design	976,317	Flight Hardware Production (2 units)	721,004
Subcontractor General and Administrative	504,756	Subcontractor G&A	121,841
Subcontractor Fee	211,861	Subcontractor	51,274
Program Management	73,224	Program Management	17,972
System Engineering	307,540	Sustaining Engineering	25,901
Development Test	201,121		
Qualification Test	148,400		
Reliability Test	239,198		
AGE	1,079,807		
Tooling	226,506	Sustaining Tooling	22,333
Non-accountable Test Hardware	97,632		
Specifications, Vendor Coordination and Procurement Expense	797,651	Specification, Vendor Coordination and Procurement Expense	204,698
System Integration	489,135	System Integration	94,486
Prime's Testing	478,395		
Minor Subcontracts	22,455	Minor Subcontracts	61,978
Total	5,853,998		1,321,487

Total Circulating KOH Electrolysis System Cost = 1,321,487 + 5,853,998
= 7,175,485 dollars

SECTION 5

PROTOTYPE COST ESTIMATING

Experience has indicated that the development cycle of a typical life support subsystem requires 3 to 5 years to bring the system from the working model to the stage where it is satisfactory for use in a low fidelity prototype configuration, as an integrated unit in manned tests. Once proven operational in integrated manned tests, the development of the system may then proceed to the high fidelity prototype or to the flight qualified status.

It may be convenient then to indicate the status of development of a life support system by one of the following four major milestones:

1. Working Model: This is an operational bench type unit built to prove feasibility and/or conceptual arrangement of system components. This unit comprises many commercial or laboratory type components. A working model is usually tested alone or in combination with a few related components.

2. Low-Fidelity Protytype: Developed to prove operational performance when integrated with an operational life support system, which is customarily tested in a manned simulator run. A low-fidelity prototype is made mostly of flight-type, but not of flight weight hardware, and usually comprises some commercial type components.

3. High-Fidelity Prototype: This is a flight-qualifiable unit, developed as a flight article, but has not undergone qualification testing. A high-fidelity prototype is expected to operate as well as a flight unit, but is not guaranteed to withstand flight launch stresses. The high-fidelity prototype may be operated to obtain actual reliability and maintainability data, if unaffected by gravity forces.

4. Flight Qualified Subsystem: This is an actual flight hardware developed for flight in a manned spacecraft.

The use of the above arrangement will help to facilitate estimating the cost of technology advancements needed prior to the development of the high-fidelity prototype hardware. Prototype cost estimates developed in this report are assumed to be for the development of one specific type of a system of a given size. For example, cost estimates are made for a six-man size SPE electrolysis system. Such estimates should not be construed to include other sizes or types of electrolysis systems. The cost of the needed technology advancement of a six-man SPE electrolysis system may thus indicate either the costs of a working model and a six-man low-fidelity prototype, or just the cost of the low-fidelity prototype if a satisfactorily working prototype had already been developed.

The methodology used in estimating the cost of a high fidelity prototype was based on the assumption that a high fidelity prototype has the same degree of hardware sophisitcation as a flight article but does not require ground support or qualification and reliability testing. Additionally, no tooling, test hardware or prime contractor integration are required. Figure 6, obtained from the results of study NAS9-9018, shows the categories and approximate percentage distribution for representative life supporr components. The cost of a high-fidelity prototype would be exclusive of qualification test, reliability test, AGE, test hardware, tooling, G&A, fee and prime contractor costs. Thus the cost of the items alloted to functions used in the development of a high-fidelity prototype may be summarized as follows:

	%	
1. Engineering Design	12.6	
2. System Engineering	4.0	
3. Development Testing	2.6	
4. First Unit Fabrication Cost	2.5	
5. Program Management	1.0	
Total	22.7%	of qualified subsystem cost

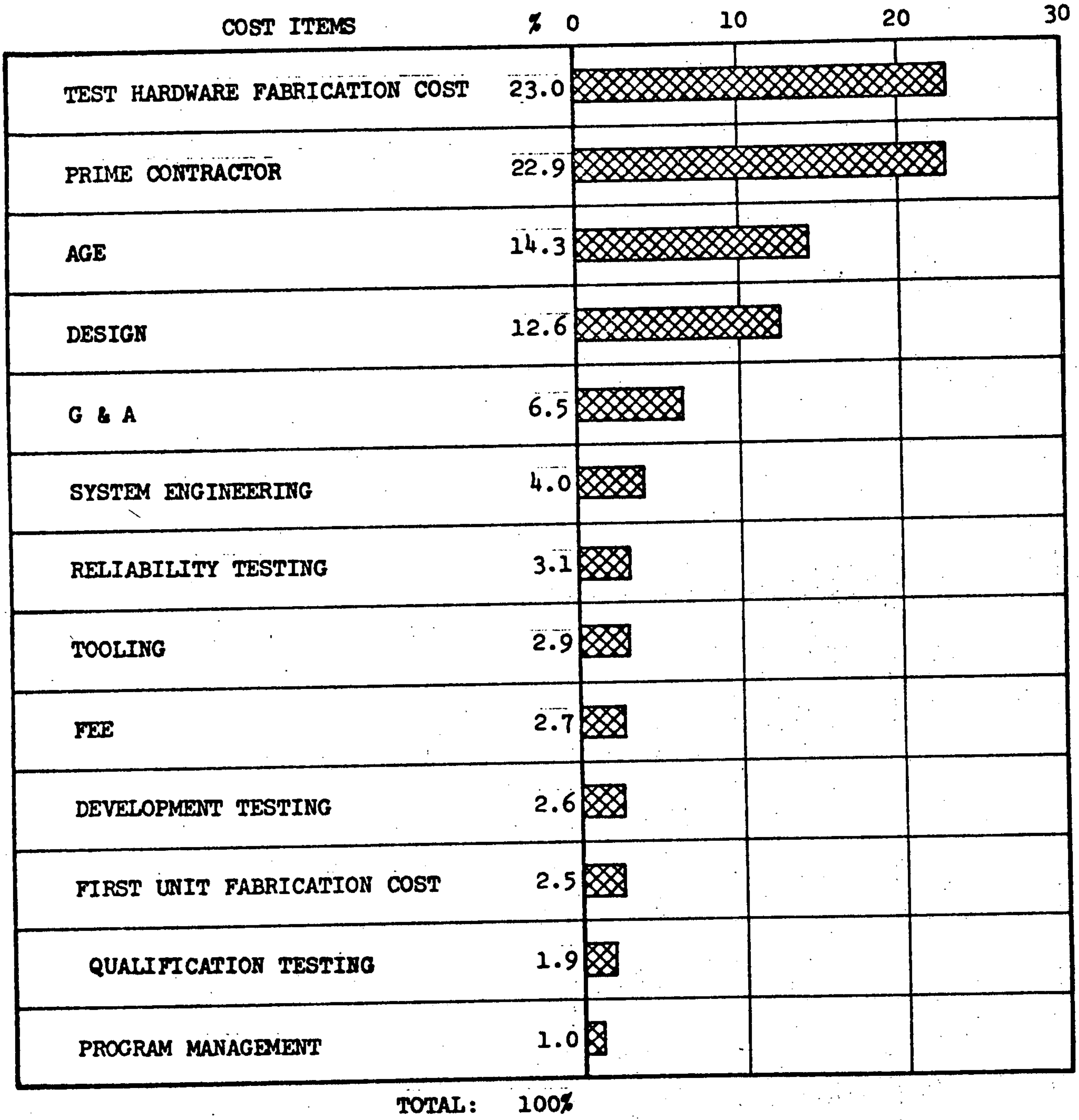

FIGURE 6 REPRESENTATIVE LIFE SUPPORT SYSTEM EXPENDITURE BREAKDOWN (FIRST FLIGHT UNIT DEVELOPMENT COST)

However, in addition to the exclusion of the major cost items mentioned above, the data in NAS9-9018 indicated that in analyzing development/cost overlays with respect to the status of design at the delivery of the first test unit, approximately 38% of the design cost has been expended at this point in time. Applying this factor to Engineering Design System Engineering, Development Test, and Program Management results in an approximate cost of a high fidelity prototype unit. That percentage cost is as follows:

		%
1.	Engineering	4.8
2.	System Engineering	1.5
3.	Development Testing	1.0
4.	First Flight Unit Fabrication Cost	2.5
5.	Program Management	0.4
		10.2% of qualified subsystem cost.

The cost of a high-fidelity prototype thus approximately equals 10.2% of the total flight hardware cost. It should be noted that qualified system cost should include qualified units developed for back-up and/or testing purposes. Experience with recent and current space progrrams indicate that 1 to 3 additional units were procured along with each flight unit. In this study, one back-up unit is included with each flight unit. The high-fidelity model cost may thus be considered to average approximately 10.2% of the cost of the qualified subsystem including one back-up unit. A table giving subsystem cost breakdown is shown at the end of the discussion of each subsystem. The total cost of the qualified subsystem is also shown in each table.

The cost of a low-fidelity prototype is less tangible than that of a high-fidelity prototype. The degree of sophistication of the low-fidelity prototype and its utilization of available space hardware and/or commercial components would tend to vary the cost of the unit. However, a value of approximately half of the cost of the high-fidelity prototype, or 5% of the qualified subsystem cost is considered an appropriate approximation.

Cost of working models were seen to vary by as much as 1000% for certain subsystems, depending on workmanship and budgetary considerations. The number of variables associated with estimating the cost of a working model usually result in a highly unreliable estimate even on an approximate basis. Accordingly, no attempt has been made in this study to establish cost estimates for working models. Table IX gives the cost breakdown of high fidelity oxygen recovery subsystems. Cost estimates of low fidelity prototype are also given in the table.

TABLE IX - PROTOTYPE COST ESTIMATES

COST ITEM	SABATIER CO_2 REDUCER	BOSCH CO_2 REDUCER	SPE ELECTROLYSIS SYSTEM	CIRCULATING KOH ELECTROLYSIS SYSTEM
Engineering Design	211,699	222,783	398,661	344,423
Program Management	17,642	18,565	33,222	28,702
System Engineering	66,156	69,620	124,582	107,632
Development Testing	44,104	46,413	83,054	71,755
First Flight Unit Fabrication Cost	110,259	116,033	207,636	179,387
High Fidelity Prototype Cost	449,860	372,313	837,144	731,899
Low Fidelity Prototype Cost	220,500	232,100	415,300	385,800